Prey Fields and Habitat of Deep Divering Odontocetes: 3D Characterization and Modeling of Beaked and Sperm Whale Foraging Areas in the Tongue of the Ocean

Douglas P. Nowacek
Duke University
Nicholas School of the Environment & Pratt School of Engineering
135 Duke Marine Lab Rd.
Beaufort, NC 28516
phone: (252) 504-7566 fax: (252) 504-7648 email: dpn3@duke.edu

Louis St. Laurent
Physical Oceanography
Woods Hole Oceanographic Institution
Woods Hole, MA
(508) 289-2753 email: lstlaurent@whoi.edu

David J. Moretti
Digital Signal Processing
Engineering, Test and Evaluation Department
Naval Undersea Warfare Center Division
Newport, RI
phone: (410) 832-5749 email: d.j.moretti@ieee.org

Patrick N. Halpin
Duke University
Nicholas School of the Environment
Durham, NC 27708-0328
phone: (919) 684-8741 email: phalpin@whoi.edu

Award Number: N00014-08-1-1162
http://www.nicholas.duke.edu

LONG-TERM GOALS

The physical and biological characteristics of the areas inhabited by deep diving odontocetes are poorly understood. Our long term goals are: i) to measure and characterize the biomass in areas and at depths inhabited by beaked and sperm whales; ii) to measure and characterize the physics of these environments; iii) to assemble the characteristics measured (i) and (ii) into a depth integrated, 3-dimensional habitat model; the model will include other dependent and independent data, e.g., chlorophyll and depth, respectively. Our final long term goal is to then apply the habitat model produced to other geographic areas to assess their likelihood as beaked and sperm whale habitat.

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **30 SEP 2011**	2. REPORT TYPE	3. DATES COVERED **00-00-2011 to 00-00-2011**
4. TITLE AND SUBTITLE **Prey Fields and Habitat of Deep Divering Odontocetes: 3D Characterization and Modeling of Beaked and Sperm Whale Foraging Areas in the Tongue of the Ocean**		5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Duke University ,Nicholas School of the Environment,Durham,NC,27708**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR’S ACRONYM(S) 11. SPONSOR/MONITOR’S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release; distribution unlimited**		
13. SUPPLEMENTARY NOTES		
14. ABSTRACT		
15. SUBJECT TERMS		

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**6**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

OBJECTIVES

The past year has been spent in three primary tasks: i) ongoing analyses of data collected and preparation of publications from the these data, which are primarily from two sources – cruises in 2008 in the Bahamas and several cruises off Cape Hatteras concurrent with tagging of short-fin pilot whales (*Globicephala macrorhynchus*) near the Cape Hatteras shelf break.

The technical objectives were: i) to develop statistical models for echoes generated by mutli-frequency scientific echosounders; ii) to compare beaked whale echolocation activity during periods when our echosounders were off vs on; and iii) collect data on prey fields and physical oceanography concurrent with multi-sensor tagging of short finned pilot whales near the Cape Hatteras shelf break; and iv) to develop Bayesian state-space animal movement models that can be used in the overall habitat models.

DTAG Movement analysis
In the spring 2011, we began to investigate new modeling approaches to the dead reckoning, georeferencing, and path estimation of DTAG deployments. More accurate path estimation and explicit accounting of the error inherent dead reckoning will enable the direct link between predator behavior and concurrent prey densities. Using deep diving pilot whales tagged off the coast of the Island of Hawaii, research began applying Bayesian state-space models to the estimation of speed parameters and the accounting of the error budget in the dead reckoning process. This work continued into summer 2011, when the work was conducted in collaboration with WHOI faculty under the supervision of Peter Tyack. This work is being conducted under the sub-award to Dr. Pat Halpin, whose lab is responsible for assembling the habitat models that are part of this project.

Statistics from Echoes generated by Scientific Echsounders
Over the last two years, a Ph.D. student at WHOI (Wu-Jung Lee) has been investigating a statistical approach to understanding the echoes generated by the scientific echosounders. This portion of the project seeks to understand more of what is in the water column from the echoes, i.e., adding to the normal ‘frequency differencing’ techniques currently in use to differentiate targets.

APPROACH

During the past year, we have worked in analytical as well as data collection modes. Our analyses and synthesis of the prey field and echolocation data from TOTO has resulted a publication in PLoS ONE (Hazen et al., 2011). St. Laurent and his group have analyzed much of the physical data from the TOTO experiment, and their results are represented the M.Sc. thesis completed by Jay Hooper (Hooper 2011 – attached). Finally, we recently collected EK60, ADCP and CTD data in the waters of the shelf break near Cape Hatteras, concurrent with attachment of DTAGs.

The EK60 system makes measurements of the returned energy from one or more targets, which are required to obtain accurate biomass estimates from the total returned echo energy (Foote, 1980a; Foote and Traynor, 1988). The amount of backscattered energy from a single fish is the backscattering cross section or echo intensity. If echo intensity is measured on a log scale it is called target strength (TS). Target strengths are often measured during surveys (*in situ*) or predicted from trawled fish lengths using a TS-fish length regression. Target strength regression equations allow prediction of TS but require large sample sizes, measurements of fish length, and often only include one variable explicitly. For example, if the tilt distribution of a school of fish differs from the tilt distribution of the fish used to derive target strengths, a consistent difference in tilt angle could bias abundance estimates.

Converting an acoustic size to a numerical size or the total returned energy to an acoustic abundance estimate relies upon appropriate target strength values for the population.

When fish echoes are too dense to be counted, target strengths are required to convert reflected echo energy to a numerical estimate. The linearity principle as defined by Foote (1983) states that the total returned energy or integrated echo can be divided by a representative backscattering cross section to estimate fish abundance. Fish lengths (L) are used in size-dependent target strength equations: $TS = \beta 1 \log L + \beta 0$ (1) where $\beta 1$ and $\beta 0$ are parameters that vary among species (Love, 1971; Foote, 1980a; Midttun, 1984). This target strength equation (1) explicitly includes length.

Echo Statistics in Mixed Assemblages

Also as part of this project, a PhD student at WHOI, Wu-Jung Lee, has developed a general theory for the echo statistics due to mixed assemblages of scatterers ensonified by scientific echosounders. For example, if there two sizes of fish interspersed and the numerical densities of the two size classes of scatterers are different, then the echo statistics is distinctly different than the traditional "expected" Rayleigh probability density function. Lee's general theory can handle an arbitrary number of size classes and numerical densities; she has drafted a paper on the topic.

For the echo statistics work, Lee has developed a general theory for the echo statistics due to mixed assemblages of scatterers. For example, if there two sizes of fish interspersed (as observed in a 2008 experiment at Georges Bank) and the numerical densities of the two size classes of scatterers are different, then the echo statistics is distinctly different than the traditional "expected" Rayleigh probability density function (PDF). Her general theory can handle an arbitrary number of size classes and numerical densities.

WORK COMPLETED

We have analyzed the prey field data and compared it with the click activity recorded concurrently by the AUTEC array (M3R); these analyses are contained in the published manuscript (Hazen et al, 2011). The physical data are being prepared for publication.

During the summer of 2010 for the second major portion of this award, we worked as part of an interdisciplinary research team to tag short finned pilot whales and measure physical and biological oceanographic data at the shelf break near Cape Hatteras, NC. We tagged 8 animals with DTAGs and during these deployments we measured backscatter with 38 and 120 kHz EK60 echosounders, the current structure with a 75 kHz ADCP, and water mass characteristics with a CTD.

In the spring 2011, we began to investigate new modeling approaches to the dead reckoning, georeferencing, and path estimation of DTAG deployments, specifically to explore these movements in areas where we have prey field data. More accurate path estimation and explicit accounting of the error inherent dead reckoning will enable the direct link between predator behavior and concurrent prey densities. Using deep diving pilot whales tagged off the coast of the Big Island of Hawaii, research began applying Bayesian state-space models to the estimation of speed parameters and the accounting of the error budget in the dead reckoning process. This work continued into summer 2011, when the work was conducted in collaboration with WHOI faculty under the supervision of Peter Tyack.

RESULTS

Our initial processing of the short-finned pilot whale shows them displaying some feeding behavior at depths where we detected layers of scatterers (Figure 1); the whales also dove to depths that did not contain dense patches or layers of prey. More analyses of these data will follow soon with publication expected within the year.

The state-space modeling work has just begun, so we have no results to report. This work will be integrated into the final habitat modeling, which will be completed in the final year of the project.

For the echo statistics work, Lee has applied the theory to broadband acoustic data collected during a September 2008 cruise over Georges Bank that was not part of the field effort for the current project. Both the net samples and resonances in our 1-6 kHz system show consistent presence of two-size-class assemblages of fish. She has applied her theory to the frequencies more relevant to the marine mammal problem, 30-70 kHz. This is driven by the need to look for cues in the acoustic echoes (such as statistical variability) for classifying in terms of the sizes and types ("type" = zooplankton vs squid vs fish, etc.. not at the species level) that echo-locating marine mammals might use to determine prey. Her initial application of the theory to the data is quite promising as can be seen in Figure 2. However, for a rigorous comparison, she needs to extend the current theory, which is specific to narrowband systems, for use with broadband data (specifically, the frequency dependence of the beampattern needs to be accounted for). She is currently busy on that extension at this point.

IMPACT/APPLICATIONS

The scientific impact of our accomplishments are likely to be significant because as far as we are aware, no field program has ever combined intensive sampling of biological and physical data in the known prey fields of a marine mammal, or any marine megavertebrate for that matter. Furthermore, we are combining animal movement information with these physical and biological maps using emerging statistical behavioral ecological models. The results reported clearly demonstrate some relationship between physical and biological parameters in areas where beaked whales prefer to forage and those they do not frequent.

RELATED PROJECTS

We have worked with M3R to share the click data from the areas where we were working, and, importantly, full audio data from the time period surrounding our work on the range to assess any potential effects our echosounders may have had on the whales. A Master's student at Duke has analyzed these data for her degree, which was completed in May 2011 (Vires 2011 and attached), but she has not yet completed publication of these results; we will submit these results for publication in the coming year.

REFERENCES

DiMarzio, N., Ward, J., and Jarvis, S. 2006. Beaked whale (*Ziphius cavirostris, Mesoplodon densirostris, Mesoplodon europaeus*) bioacoustic spatial/temporal habitat characterization in the Tongue of the Ocean, Bahamas. Program report, program element 0601152N, subproject RR00N04, Naval Undersea Warfare Center, Newport, RI.

Foote, K. G. 1980a. Averaging of fish target strength functions. J. Acoust. Soc. Am. 67: 504-515.

K.G. Foote. 1983. "Maintaining precision calibrations with optimal copper spheres, J. Acoust. Soc. Am. 73: 1054-1063.

Foote, K. G. and Traynor, J. J. 1988. Comparison of walleye pollock target strength estimates determined from *in situ* measurements and calculations based on swimbladder form. J. Acoust. Soc. Am. 83: 9-17.

Hazen EL, Nowacek DP, St. Laurent L, Halpin PN, Moretti DJ. 2011. The Relationship among Oceanography, Prey Fields, and Beaked Whale Foraging Habitat in the Tongue of the Ocean. PLoS ONE 6(4): e19269. doi:10.1371/journal.pone.0019269

Hooper, J.A. 2011. Dissipation Processes In The Tongue Of The Ocean. M.Sc. Thesis in Earth, Ocean and Atmospheric Science, Florida State University, Tallahassee, FL (http://etd.lib.fsu.edu/theses/available/etd-04202011-183124/).

Vires, G. 2011. Echosounder effects on beaked whales in the Tongue of the Ocean, Bahamas. Masters project, Nicholas School of the Environment, Duke University.

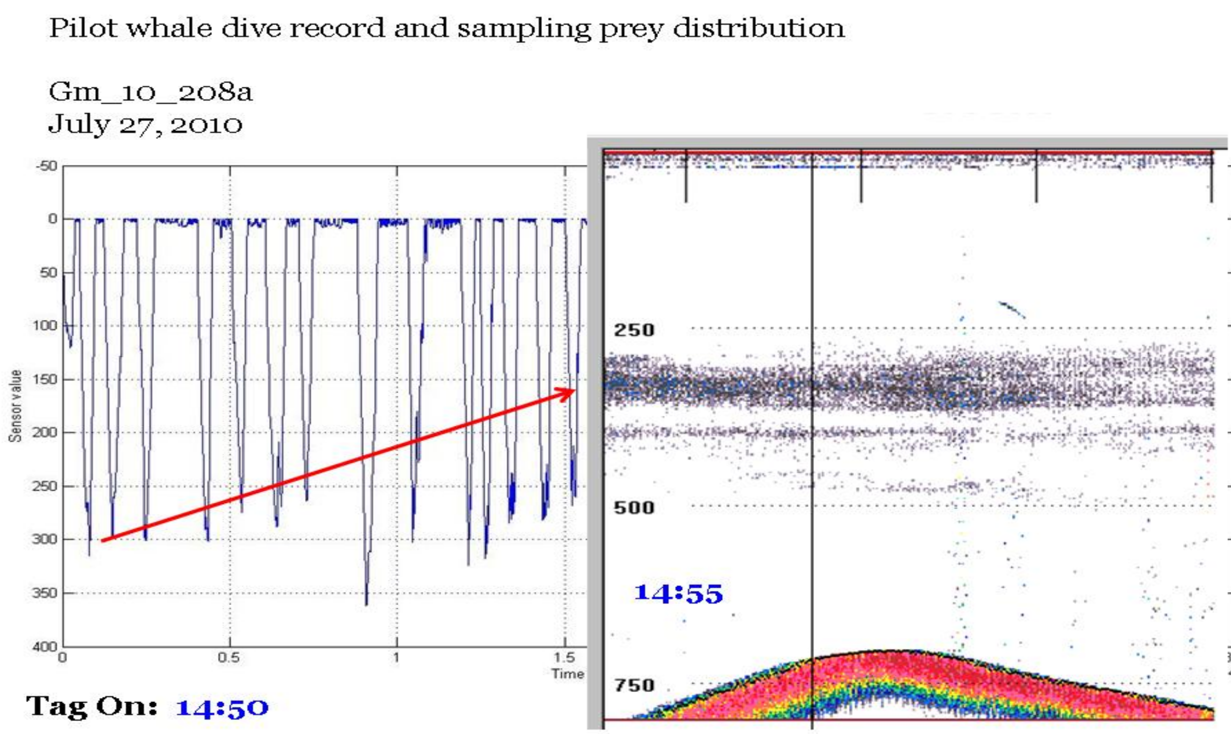

Figure 1. Time-depth records (left) for a diving short-finned pilot whale carrying a DTAG, and water column backscatter (right) generated by the 38 kHz EK60 system aboard the research vessel following the tagged whale at ~500 m. Note the dense layer of prey located at the depth to which the whale is diving; also interesting is the large apparently single target at just less than 250 m depth.

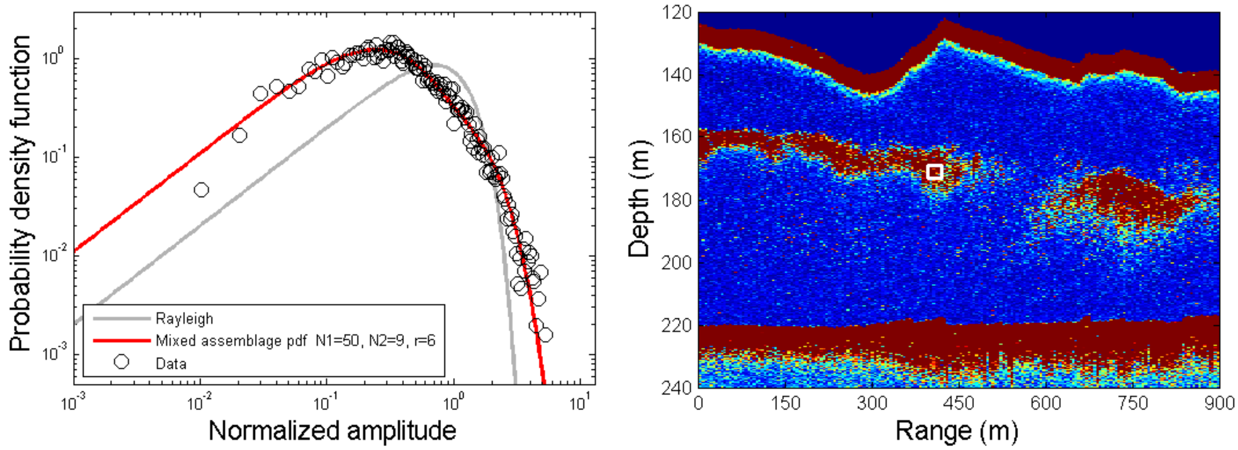

Figure 2. Echogram (right) and echo statistics (left) for assessment of target assemblage measured with 30-70 kHz echosounders on Georges Bank during a 2008 WHOI cruise.